Innovative Food Science and Emerging Technologies 62 (2020) 102350

Contents lists available at ScienceDirect

Innovative Food Science and Emerging Technologies

journal homepage: www.elsevier.com/locate/ifset

Advances in the valorization of spent brewer's yeast

Pradeep Puligundla[a,*], Chulkyoon Mok[a], Sungkwon Park[b]

[a] Department of Food Science & Biotechnology, Gachon University, 1342 Seongnam-daero, Sujeong-gu, Seongnam-si, Gyeonggi-do 13120, Republic of Korea
[b] Department of Food Science and Biotechnology, Sejong University, 209 Neungdong-ro, Gwangjin-gu, Seoul 05006, Republic of Korea

ARTICLE INFO

Keywords:
Spent brewer's yeast
Valorization
β-Glucans
Yeast extract
Animal feed

ABSTRACT

Spent brewer's yeast (SBY) is one of the major by-products produced during beer brewing process. SBY is an abundant source of protein, minerals, vitamins, especially vitamin Bcomplex, as well as nutraceuticals such as β-glucans or mono- and oligosaccharides. Due to the presence of nutrients, abundant availability and low cost, SBY has been widely used in animal feed. However, over the last decades, considerable efforts have been devoted to the development of alternative applications for SBY, such as functional food ingredient and fermentation substrate. Therefore, the aim of this review was to provide an up-to-date overview on the valorization of SBY.

1. Introduction

Conventionally, brewer's yeast strains are divided into two categories, namely top-fermenting (ale) and bottom-fermenting (lager) yeasts. Strains of *Saccharomyces cerevisiae* are commonly used to produce ale beers in the temperature range of 16–25 °C. On the other hand, *Saccharomyces pastorianus* or *Saccharomyces carlsbergensis* strains are industrially used to produce lager beers in the temperature range of 8–15 °C (Ferreira, Pinho, Vieira, & Tavarela, 2010).

In beer brewing process, spent brewer's yeast (SBY) (also known as residual yeast or surplus yeast) is one of the predominant by-products. Other major by-products include brewery spent grain and hot trub. SBY accounts for approximately 1.5–2.5% of the total beer production (Bekatorou, Plessas, & Mantzourani, 2015). In a lager fermentation, total amount of SBY is approximately 0.6–0.8 lb./bbl (pounds per barrel) of final volume of product (Huige, 2006). SBY is an abundant and inexpensive source of protein (45–60%), minerals, Bcomplex vitamins and other worth constituents (Podpora, Świderski, Sadowska, Rakowska, & Wasiak-Zys, 2016). In addition, spent yeasts are a rich source of nutraceuticals such as β-glucans or mono- and oligosaccharides.

SBY is generally regarded as safe (GRAS) for human consumption (Ferreira et al., 2010). However, due to high levels (6–15%) of nucleic acids in their composition, SBY application in human nutrition as a protein source is limited (Podpora et al., 2016). It is well-known that high nucleic acid levels in the human diet may lead to increased blood uric acid levels and in turn can result in hyperuricemia (Podpora et al., 2016). Therefore, SBY has been conventionally used as a cheap source of protein in animal diets. Because of certain disadvantages with SBY such as low shelf life, transportation cost and requirement for further processing (Boateng, Okai, Frimpong, & Zeebone, 2015), spent yeasts are usually disposed off in the environment. Nevertheless, the valorization of SBY can be achieved through the extraction and isolation of economically important components such as proteins, amino acids, bioactives like β-glucans and functional peptides, vitamins, minerals, fiber, flavor compounds and others.

2. SBY composition

SBY contains relatively high levels of protein and low levels of reducing sugars; and total organic carbon content was estimated to be approximately 45% dry matter (DM) (Mathias, Alexandre, Cammarota, de Mello, & Sérvulo, 2015). Approximate levels (% DM) of ash content, total nitrogen and total protein in SBY were shown to be 6, 9 and 45.6, respectively; and average levels (% DM) of soluble reducing sugar, soluble nitrogen and soluble protein were estimated to be 1.3, 2.53 and 14.66, respectively (Mathias et al., 2015). In addition, the average levels of free amino nitrogen and chemical oxygen demand were calculated to be 4.09 mg/g and 1308 mg/g, respectively (Mathias et al., 2015).

3. Yeast cell disruption

Different mechanical and non-mechanical techniques can be used for yeast cell disruption. Milling and homogenization techniques fall under mechanical category. Non-mechanical techniques can be further divided into physical, chemical, enzymatic and electrical, as shown in Fig. 1.

* Corresponding author.
E-mail address: puli@gachon.ac.kr (P. Puligundla).

https://doi.org/10.1016/j.ifset.2020.102350
Received 31 December 2019; Received in revised form 6 March 2020; Accepted 31 March 2020
Available online 04 April 2020

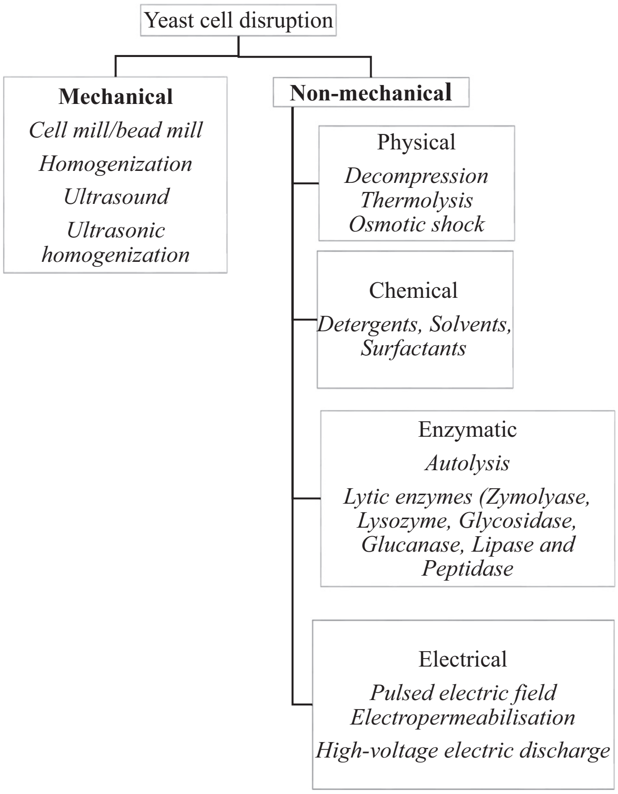

Fig. 1. Different methods for the disruption of yeast cell.
(Adapted with permission from Liu, Ding, Sun, Boussetta, and Vorobiev (2016).)

4. Potential valorization opportunities for SBY

4.1. Rich source of β-glucans

β-D-Glucans possess several physiological functions. Spent brewer's yeast (SBY) cell walls are rich in β-D-glucan. Breweries could generate additional revenue by isolating β-glucan from SBY as a high-value product. Tian, Yang, and Jiang (2019) used alkali treatment at high pressure for the isolation of β-D-glucan from SBY. They showed that, at optimal conditions, extraction rate of 78.38% with β-D-glucan content of 78.11% can be achieved. Homogenization of cell walls was found to yield higher β-glucan content (Thammakiti, Suphantharika, Phaesuwan, & Verduyn, 2004). Alkaline treatment was used to isolate particulate (water-insoluble) β-glucan from SBY cell walls and β-glucan with minimal structural changes can be obtained through the combination of sonication with spray-drying, and the formed particles exhibited insignificant agglomerates formation (Zechner-Krpan et al., 2010). For most food applications, β-glucan powders with free-flowing properties are desirable. β-Glucans can improve the functional properties of food products by acting as thickening, emulsifying, oil-binding or water-holding agents (Thammakiti et al., 2004). However, these capacities of β-glucans were shown to be affected by differences in isolation and drying procedures (Petravić-Tominac et al., 2011). They found that lyophilized preparations exhibited highest oil-binding capacity and lowest swelling and air-dried preparations showed enhanced swelling. It has also been shown that β-glucans obtained from homogenized cell walls of SBY exhibited relatively higher apparent viscosity, emulsion stabilizing capacity and water-holding capacity compared with commercial β-glucan from baker's yeast (Thammakiti et al., 2004).

β-Glucans obtained from SBY have been used in yoghurts as nutraceutical ingredient—addition up to 0.3% did not affect the structure stability and sensory quality of natural yoghurts (Piotrowska, Waszkiewicz-Robak, & Swiderski, 2009). Powdered β-glucan derived from SBY was used as a thickener in skimmed-milk yogurt (Raikos, Grant, Hayes, & Ranawana, 2018). They showed that the powder incorporation did not negatively affect most of the physicochemical properties of the yogurt. β-Glucans derived from SBY were used as functional ingredient in bread (Martins, Pinho, & Ferreira, 2018). They showed that β-glucan-rich extract contributed to improved β-glucan and dietary fiber contents in bread. In addition, β-glucans incorporated bread exhibited higher specific volume with uniform pores. Furthermore, β-glucans promoted bread crust browning. The potential of β-glucan derived from SBY as a fat replacer in mayonnaise has been shown (Marinescu, Stoicescu, & Patrascu, 2011; Worrasinchai, Suphantharika, Pinjai, & Jamnong, 2006). Marinescu et al. (2011) showed that storage stability of mayonnaise was improved with β-glucan substitution at a level of 50%. Their results concluded that SBY β-glucans can be used as emulsion stabilizer and fat replacer in mayonnaise. However, β-glucan incorporation may adversely affect sensory quality of reduced-fat mayonnaise, especially appearance and color. As a remedy to this drawback, the application of natural colorants (e.g., β-carotene and lutein) has been recommended (Santipanichwong & Suphantharika, 2007). The addition of β-glucan from SBY to starch-based food (up to 1%) was suggested to be advantageous to reduce calorie content as well as to maintain desirable textural characteristics (Yoo & Lee, 2007). β-Glucan prepared from SBY was successfully used to retard gel hardness development of rice starch/β-glucan mixed gels during long-term refrigerated storage (Satrapai & Suphantharika, 2007). Fine particulate β-glucans from SBY have been shown to contribute to strengthening of gel network formed by SBY β-glucans and κ-carrageenan (Xu et al., 2009). Their findings could be useful for developing novel foods. Applications of yeast-derived β-glucans in food production have been reviewed by Zechner-Krpan, Petravić-Tominac, Panjkota-Krbavčić, Grba, and Berković (2009).

β-Glucan-rich fraction prepared from SBY has been used as an immunostimulant in shrimp feed (Thanardkit, Khunrae, Suphantharika, & Verduyn, 2002). They showed that autolysis and further treatment with hot alkali of SBY led to the production of a fraction containing an apparent glucan content of approx. 53% (w/w). Upon short-term (3 days) feeding this impure β-glucan to shrimp at 0.2% (w/w of the feed), considerable increases in the number of haemocytes, phenol oxidase and bactericidal activity (against *Vibrio harveyi*) were observed. In another study by Suphantharika, Khunrae, Thanardkit, and Verduyn (2003), β-glucan-rich fraction originated from the insoluble cell wall fraction of SBY was shown to exert an increased phenoloxidase activity in hemolymph of black tiger shrimp under both *in vitro* and *in vivo* conditions when compared with controls. SBY β-D-glucan was used as a biological response modifier (BRM) (Liepins et al., 2015). They showed that immunogenic properties (TNF-α induction activity) of SBY β-D-glucans were improved by desiccation; furthermore, dried SBY carboxymethylated β-D-glucan was shown to induce immunoactivity similar to or exceeded that of pleuran (β-glucan from *Pleurotus ostreatus*), a well-characterized fungal BRM. β-Glucan extracted from SBY can potentially be used as a cryoprotectant for probiotic *Lactobacillus* cultures during freeze drying, storage (4 °C) and *in vitro* digestion (da Silva Guedes et al., 2019). β-Glucans isolated from SBY were found to be more effective at lowering the levels of LDL cholesterol and triacylglycerols as well as serum total cholesterol in experimental rats (Waszkiewicz-Robak & Bartnikowska, 2009). β-Glucans derived from SBY could be used for the adsorption of mycotoxins since β-D-glucans isolated from yeast cell walls have been shown to exhibit a good adsorption capacity for zearalenone (alkali-insoluble fraction: up to 50%; alkali-soluble fraction: ~16%) (Yiannikouris et al., 2004).

4.2. Source of proteins and functional peptides

SBY extracts are rich in proteins (Vieira, Cunha, & Ferreira, 2019). Yeast cell disruption is a crucial step for maximum protein recovery.

The potential of subcritical water to hydrolyze SBY cells and subsequent recovery of proteins and amino acids has been shown (Lamoolphak et al., 2006). They showed that, with an increase in temperature of the water, the yield of protein increased and the yield of amino acids decreased; the maximum amino acid and protein yields obtained were 0.063 and 0.16 mg/mg of dry yeast, respectively. Marson, da Costa Machado, de Castro, and Hubinger (2019) compared conventional approaches (autolysis and mechanical rupture) with enzymatic hydrolysis for the isolation of proteins. Their results showed that sequential enzymatic hydrolysis (with Brauzyn® and Alcalase™) resulted in maximum protein yield and antioxidant properties. Amorim et al. (2016) obtained peptide concentrates from hydrolyzed SBY proteins via filtration. They showed that peptide extracts, especially low molecular weight peptide fraction (< 3 kDa), exhibited significant antiulcer activity. In addition, they showed the antiproliferative activity of the extracts against leukemia cells. In another study, Amorim, Pinheiro, and Pintado (2019) have optimized SBY autolysis and subsequent hydrolysis processes by response surface methodology for the generation of stable angiotensin converting enzyme (ACE)-inhibitory peptides. They found that a peptide fraction (< 3 kDa) exhibited potent ACE-inhibitory activity and superior *in vitro* gastrointestinal stability. Their results indicated that SBY can be used as a source of ACE-inhibitory peptides, which are well-known to exhibit antihypertensive effect. For effective separation of polysaccharide and protein from SBY extract, the use of ultrafiltration technology has been recommended (Huang, Gao, Ma, & Lu, 2012).

4.3. Autolysis and functional quality

Enzymatic treatment of SBY during autolysis has been shown to improve functional quality of extracts derived from SBY. Cao et al. (2017) showed that pretreatment with β-mannanase during SBY autolysis had substantially enhanced the yield of SBY extracts through improved cell wall degradation (polysaccharides were converted into oligosaccharides). In addition, enhanced antioxidant activity was noted in the enzyme-pretreated extracts. Autolysis of SBY extract (from inner cell content) was optimized by response surface methodology in order to obtain SBY autolysate possessing enhanced ACE-inhibitory and antioxidant properties (Vieira, Melo, & Ferreira, 2017). Efficient *in vitro* absorption of bioactive compounds from SBY autolysate has been shown (Vieira et al., 2016). A two-step autolysis has been shown to be result in improved amino acid yield from SBY (Boonyeun, Shotipruk, Prommuak, Suphantharika, & Muangnapoh, 2011).

4.4. Functional food ingredient

SBY extracts have been shown to be a promising source of bioactive ingredients, since they contain well-balanced amino acid profile along with other functional constituents such as phenolic acids, flavonoids, carotenoids and peptides (Vieira et al., 2019). SBY autolysate was supplemented to improve the nutritive value of beetroot and carrot juices (Rakin, Vukasinovic, Siler-Marinkovic, & Maksimovic, 2007). They showed that the autolysate contributed for improved lactic acid production and the fermented juices possessed enhanced levels of minerals, pigments and vitamins. The incorporation of SBY extract (1%) as additive has shown to improve free amino acid and protein contents, chewiness and hardness (acts as gel stabilizer) of cooked ham (Pancrazio et al., 2016). Yeast extracts rich in essential amino acids, low molecular weight peptides, and with high antioxidant activities were prepared from SBY (Podpora et al., 2016). They suggested that these extracts could be used for the design of dietary supplements and functional foods. SBY hydrolysate rich in Cyclo-His-Pro (CHP) content was prepared by enzymatic hydrolysis and the hydrolysate showed significant antioxidant and/or antidiabetic properties (Jung et al., 2011), and therefore it can potentially be used for the preparation of functional foods.

Yeast mannoproteins are approved food additives, especially as a stabilizer in wine. SBY has been shown to be a viable biomaterial for obtainment of extract rich in mannoproteins (Costa, Magnani, & Castro-Gomez, 2012). They showed that the extract exhibited good emulsification activity and emulsion stability. Mannoprotein derived from SBY has the potential to be used as an emulsifier/stabilizer in French salad dressing (de Melo, de Souza, da Silva Araujo, & Magnani, 2015). They showed that salad dressing prepared with mannoprotein derived from spent *Saccharomyces uvarum* exhibited the highest scores for color, flavor, taste and overall acceptance. In another study, β-glucan and mannoprotein were extracted from SBY cell wall with satisfactory purity and high yields (da Silva Araújo et al., 2014). They showed that the obtained mannoprotein possessed good stabilizing and emulsifying properties, and can potentially replace xanthan gum in mayonnaise formulations without negatively affecting their sensory properties during refrigerated storage.

SBY, especially from craft brewery, contains hop acids (isoα-, α-, and β-acids) at elevated levels (Bryant & Cohen, 2015). These acids are known to have antibacterial, antioxidant, anticancer, and anti-inflammatory activities, and therefore spent craft brewer's yeast could be used as a valuable functional food ingredient.

4.5. Yeast extract

For the production of yeast extracts, SBY has been shown to be a nutrient-rich and cost-effective starting material (Jacob, Striegel, Rychlik, Hutzler, & Methner, 2019a). Their results also showed that the composition of SBY influences the proportion of physiologically important ingredients of yeast extract. Yeast extract from SBY was produced by autolysis, which was induced through incubation at elevated temperatures for different durations (Tanguler & Erten, 2008). Their results indicated that yeast extract with considerable levels of protein and α-amino nitrogen can be obtained from autolysis at 50 °C for 24 h. In another study by Jacob, Striegel, Rychlik, Hutzler, & Methner (2019b), for superior quality yeast extract production, cell disruptions by cell mill and sonotrode methods have been shown to be effective alternatives to traditional autolytic method. They showed that yeast extract produced by the mechanical methods contained relatively high levels of protein, fat, trehalose, Bvitamins, especially biologically active 5-methyltetrahydrofolate. SBY extract has been shown to be rich in protein, low in fat and moisture contents; and a potential source of essential amino acids as well as flavor enhancing amino acids (glycine, alanine, glutamic acid and aspartic acid) (Vieira et al., 2016). In addition, the extracts were shown to contain macrominerals (K, Na, Ca, Mg) trace elements (Zn, Fe, Mn, Cu, Cr, Co, Mo, Se) and vitamins (B3, B6 and B9). Yeast extract prepared from SBY has been used for growth and sporulation of *Bacillus thuringiensis* subsp. *kurstaki*, a well-known biological control agent against lepidopterans (Saksinchai, Suphantharika, & Verduyn, 2001). They showed that Fe was a limiting nutrient in the extract for complete sporulation to occur. The nutritional composition of SBY extract is given in Table 1.

4.6. Fermentation substrate

SBY has considerable potential to be used as additive in fermentation media because of its low C/N ratio (Mathias et al., 2015). SBY was used as alternative growth medium for the production of proteolytic enzyme via lactic acid bacteria cultivation (Mathias, de Aguiar, de Almeida e Silva, de Mello, & Sérvulo, 2017). They showed that SBY was the most suitable substrate among other brewery wastes for extracellular enzyme production, and glucose supplementation exerted a positive effect on the enzyme production since residual yeast are low in fermentable sugars (Mathias et al., 2015). For improving fermentation efficiency in home brewing or other settings, Vegemite (food spread manufactured from SBY extract) or other yeast extract spreads have been suggested as potential sources of readily available and inexpensive

Table 1
Mean values of nutritional composition of spent brewer's yeast (SBY) extract.
(Adapted with permission from Vieira, Carvalho, et al. (2016).)

Proximate composition	(g/100 g dw)
Moisture (%)	7.7
Protein	64.1
α-amino nitrogen	3.7
Carbohydrates	12.9
Fat	1.3
Ash	14.0
Ribonucleic acid (RNA)	4.0
Macrominerals	(mg/100 g dw)
Potassium (K)	9148
Sodium (Na)	1228
Magnesium (Mg)	273
Calcium (Ca)	27
Trace elements	(mg/100 g dw)
Chromium (Cr)	0.019
Copper (Cu)	0.364
Cobalt (Co)	0.03
Manganese (Mn)	0.564
Iron (Fe)	1.76
Selenium (Se)	0.030
Zinc (Zn)	11.9
Molybdenum (Mo)	0.003
Vitamins	(mg/100 g dw)
Nicotinic acid (B3)	77.2
Pyridoxine (B6)	55.1
Folic acid (B9)	3.01
Riboflavin (B2)	< 0.32
Cyanocobalamin (B12)	< 0.25

nutrients (Kerr & Schulz, 2016). SBY has been used as one of the fermentation nutrients for the production of ACE-inhibitory proteins from *Ganoderma lucidum* mycelia (Mohamad Ansor, Abdullah, & Aminudin, 2013). The potential of SBY extract for cost-effective fermentative production of succinate has been shown (Sawisit et al., 2012). They showed that a final yield of 68.73% can be achieved by using glucose or lactose medium supplemented with SBY extract at 5 g/L. Enzymatic hydrolysate of SBY as a nitrogen source has been shown to successfully replace yeast extract for succinic acid production in glucose-containing media (Jiang et al., 2010) and in corn fiber hydrolysate (Chen et al., 2011) by *Actinobacillus succinogenes* NJ113. In both the studies, vitamins supplementation further enhanced the succinic acid yield.

4.6.1. Ethanol fermentation

SBY was used as a nutrient adjunct in ethanol fermentation using corn mashes (Pietrzak & Kawa-Rygielska, 2013). They showed that, depending on the level of SBY addition (0.1 to 5.0% w/w), the rates of sugar consumption and ethanol production were accelerated; and 6.5 to 11% improvement in overall ethanol yield was noted by the supplementations. SBY was supplemented as a nutrient source in a very high gravity (VHG) ethanol fermentation using maize mashes (Kawa-Rygielska & Pietrzak, 2014). They showed that SBY and derived products (spray dried yeast and yeast extract) supplementation led to increased ethanol production rates, ethanol yield and decreased fermentation time. Yeast extract produced by SBY autolysis (A-YE) was used as a substitute for commercial yeast extract in VHG ethanol fermentation of cassava starch (Palasak, Sooksai, & Savarajara, 2019). They showed that an ethanol yield of 115.77 g/L can be obtained in 24 h by the supplementation of 5.23 g/L of A-YE. For ethanol production, SBY was used as a low-cost feedstock (as inoculum) along with two other agro-industrial wastes, namely soft-drink industry wastewater as carbon source and corn steep water as nitrogen source (Comelli, Seluy, Benzzo, & Isla, 2018). They showed a complete utilization of sugars in the wastewater in < 8 h at optimal conditions, with 0.45 $g_{ethanol}/g_{sugar}$ ethanol yields. Despite these merits, SBY supplementation may lead to high concentrations of maltodextrins (un-fermentable by yeast) in mashes, and therefore, limiting the addition or additional treatment has been suggested to alleviate the disadvantage (Kawa-Rygielska & Pietrzak, 2014).

4.6.2. Renewable energy

SBY has been shown to be a viable source for methane (biogas) production through anaerobic digestion and SBY source influenced the biogas composition (Sosa-Hernández, Parameswaran, Alemán-Nava, Torres, & Parra-Saldívar, 2016). In another study, specific methane production and solubilization rate constant for SBY in fed-batch stirred reactors (5 L) were reported to be 0.255 L methane per gram of COD and 0.659 d^{-1}, respectively (Vitanza, Cortesi, Gallo, Colussi, & De Arana-Sarabia, 2016). Because of its rapid solubilization, SBY could be used as an effective substrate for co-digestion purposes. SBY as a co-substrate was successfully used for methane generation from swine manure via anaerobic digestion (Spajic et al., 2010). SBY along with spent grain have been used as substrates for methane production through anaerobic digestion (Oliveira, Alves, & Costa, 2018). They showed that the combination of the substrates was more promising than individual substrate digestion in terms of produced methane volume; and maximum methane generation and biodegradability can be achieved by the addition of crude glycerol as co-substrate to these substrates. In another study, bio-oil and granular activated carbon were produced using SBY and brewer's spent grain through pyrolysis and CO_2 activation (Gonçalves, Nakamura, Furtado, & Veit, 2017).

4.6.3. Lactic acid fermentation

SBY was used as an inexpensive nitrogen source in L-(+)-lactic acid fermentation using brewer's spent grain (BSG) hydrolysate (Pejin et al., 2019). They showed that free amino nitrogen (FAN) concentration of the medium was significantly increased by SBY addition. In addition, the yield of L-(+)-lactic acid was reported to be 89% with 50 g/L of SBY. Brewing by-products, namely brewer's spent grain and SBY, along with malting and oil industry by-products (malt rootlets and soy lecithin, respectively) have been used as substrates in L-(+)-lactic acid fermentation (Radosavljević et al., 2019; Radosavljević et al., 2020). They found that the combination of these by-products formed an inexpensive and appropriate medium for lactic acid fermentation.

4.7. Feed ingredient

4.7.1. Aqua feed

Dietary supplementation with SBY was shown to improve digestive capacities of white seabream and meagre fish species (Castro et al., 2013). They showed that, with 2% SBY diet, improved protease and amylase activities were observed in the intestine and the pyloric caeca of white seabream. In addition, enhanced lipase activity in the pyloric caeca was noted. On the other hand, enhanced amylase activity was noted in the pyloric caeca of meagre with the supplementation. The potential of SBY as a fish meal alternative in diets for giant freshwater prawn has been shown (Nguyen et al., 2019). Their results showed that up to 60% of fishmeal protein in the diet of the prawn can be substituted by SBY.

4.7.2. Animal feed

SBY as a protein supplement has long been incorporated in ruminant diets. It has been demonstrated under *in vitro* conditions that craft beer SBY, which contain antimicrobial α- and β-acids, as a protein supplement can prevent excessive rumen protein degradation by rumen hyper-ammonia producing bacteria (Harlow, Bryant, Cohen, O'connell, & Flythe, 2016). Black soldier fly (*Hermetia illucens*) larvae, a potential protein source for animal feed, can feed on a wide variety of wastes. It has been shown that the larvae of black soldier fly that fed on spent grain-based diet supplemented with SBY exhibited relatively high wet weight with short doubling time compared with larvae fed unsupplemented diet (Chia et al., 2018a). SBY in combination with brewers' spent grain and cane molasses were used as substrates for black soldier fly larvae production, which were intended to use as an alternative protein source in aquaculture and livestock feed (Chia et al., 2018b). The incorporation of SBY in pig diet resulted in significantly decreased total cholesterol and blood urea nitrogen in pigs (Sreeparvathy & Anuraj, 2018). They also showed a significant enhancement in apparent magnesium (Mg) availability with SBY incorporation.

It has been shown that corn meal in sheep diet can be substituted up to 100% with SBY without negatively affecting feed intake, feeding behavior and digestibility (Oliveira et al., 2016). SBY in combination with other brewery by-products, namely brewer's spent grain with hot sludge and protein sludge from press liquor, were found suitable for the preparation of protein-rich feed for laying hens (Levic, Djuragic, & Sredanovic, 2010). They showed that the formulated feed exerted superior effect on reproductive performance of laying hens compared with soybean meal. SBY can also replace fish meal as a protein source and can be supplemented in pig diets upto 6% without detrimental effects on performance (Kabugo, Mutetikka, Mwesigwa, Beyihayo, & Kugonza, 2014). In another study, Gondwe, Mtimuni, and Safalaoh (1999) showed that the substitution of vitamin premix with sun-dried SBY in broiler finisher diets exerted significant positive effects in terms of weight gains and live weights, especially in Indian River chickens, compared with birds of control group. In order to improve immune system, the supplementation of ribonucleic acid (RNA) isolated from SBY into cattle feed and human nutrition has been suggested (Chládek, Přikryl, & Zeman, 2007).

4.8. Source of enzymes

Proteases derived from SBY have been used for the production of sardine protein hydrolysates (Vieira, Pinho, & Ferreira, 2017). They showed that, in viscera hydrolysate resulted from SBY proteases treatment, proteins exhibited improved functional properties, including oil-binding capacity, foaming and emulsifying ability. Proteases extracted from SBY were used to hydrolyze sarcoplasmic proteins of sardine by-products and the resultant hydrolysates were shown to possess ACE-inhibitory activity and antioxidant activity (Vieira & Ferreira, 2017). They concluded that two different agro-industrial by-products can be simultaneously valorized through this approach. Proteases from SBY have also been used for the preparation of sardine protein hydrolysate having anti-inflammatory effects (Vieira, Van Camp, Ferreira, & Grootaert, 2018). Their results suggested that the hydrolysate has the potential to be used as a functional food. SBY proteases were used to hydrolyze brewers' spent grain proteins and the resultant hydrolysates exhibited anti-cytotoxic activity (Vieira, da Silva, Carmo, & Ferreira, 2017).

4.9. Source of nucleic acids

SBY is one of the cheapest sources of nucleic acids. For the preparation of flavor-enhancing 5′-nucleotides, SBY has been shown to be an interesting starting material (Sombutyanuchit, Suphantharika, & Verduyn, 2001). It is known that the interaction of 5′-nucleotides synergistically with amino acids (especially glutamic acid) and peptides in yeast extract leads to taste improvement. It has been shown that, for the purpose of intumescent flame retardant coating on cotton fabrics, nucleic acids extracted from SBY can potentially replace expensive, purified low molecular weight DNA (Bosco, Casale, Gribaudo, Mollea, & Malucelli, 2017). Their results concluded that SBY-derived nucleic acids can impart self-extinction to cotton.

4.10. Biosorption

SBY was shown to be an excellent biosorbent for the removal of lead (Pb) from aqueous solution (Duda-Chodak, Tarko, & Milotta, 2012). Their results showed that SBY can remove > 90% of Pb in the solution (from 200 to 500 mg Pb/dm^3 to 1 mg/dm^3) in < 20 min. Modified spent yeast was successfully used as a flocculant for harvesting microalgae *Chlorella vulgaris* (Prochazkova, Kastanek, & Branyik, 2015). They showed that highly effective cationic flocculant (> 90% harvesting efficiency) can be developed by surface modification (by treatment with 2-chloro-N, N-diethylethylamine hydrochloride) of microparticles prepared from SBY. Bentonite clay functionalized with spent brewer's yeast was used to recover platinum group metals from wastewater (Mosai, Chimuka, Cukrowska, Kotzé, & Tutu, 2020). Their results suggested that a maximum removal efficiency of 98.5% can be achieved.

5. Miscellaneous applications

SBY could potentially be used as a reducing agent in 'green' synthesis of nanoparticles. SBY has been used for silver nanoparticles (AgNPs) production (Yantcheva et al., 2019). A relatively quick synthesis of AgNPs was observed when non-pasteurized and pasteurized SBY combined with aqueous extract of *Rosa damascena* waste, which is rich in polyphenolic substances.

Carotenoids are widely used as natural dyes in the food industry. SBY along with a by-product of biodiesel production, raw glycerin, was used for microbial production of carotenoids (Rodrigues, Schueler, da Silva, Sérvulo, & Oliveira, 2019). They showed that total carotenoids as high as 420 μg/g can be produced. These results indicate that carotenoids as natural dyes can be produced biotechnologically using SBY as a substrate.

Phytostimulatory effect of SBY has recently been shown. SBY can be used as an elicitor for rye microgreen cultivation (Ana, Andrei, Mircea, Cristina, & Cristina, 2017). They showed that SBY treatment exerted increased germination, fresh mass and plantlet growth. In addition, total phenolic contents and antioxidant activity were enhanced by the treatment.

To decrease atmospheric CO_2 levels, the production and addition of degradation-resistant biochar to soils offers a hopeful way. George, Wagner, Kücke, and Rillig (2012) showed that the addition of hydrochar produced from SBY exhibited positive effects on soil aggregation. However, arbuscular mycorrhizal fungi root colonization was negatively affected by the hydrochar addition.

SBY was used as raw material for the preparation of a protein foaming agent for concrete (Liu, Huo, Lei, & Li, 2010). They showed that foam retaining duration can be extended by the addition of carrageenan to foaming solution.

Different proportions of SBY along with sucrose were supplemented as components in diets used for rearing the Mediterranean fruit fly larvae intended for insect pest control (for the production of sterile male in the sterile insect technique) (Nestel & Nemny-Lavy, 2008).

SBY could be used for the production of small molecules. SBY was successfully used for the co-production of S-adenosyl-L-methionine and glutathione, with productivities of 40–45 and 13–18 mg/g dry cell weight, respectively (Liu, Lin, Cen, & Pan, 2004).

There has recently been increasing interest in the production of edible insects for human consumption. The potential application of SBY along with other feed ingredients, such as spent grains, cookie remains, wheat bran, soy, rye, oats, etc., for the successful rearing of edible insects has been shown (Halloran, Roos, Eilenberg, Cerutti, & Bruun, 2016).

For cultivating animal cells *in vitro* in basal media supplemented without or with reduced fetal bovine serum, yeast extract derived from SBY along with other inexpensive substrates might be used.

A summary of various valorization opportunities for SBY, which are discussed above, is given in Table 2.

6. Concluding remarks

Economic viability is a key factor for the commercial success of any

Table 2
Summary of various valorization opportunities for SBY.

Valorized product/valorization route	Application
β-Glucans	◆ Emulsion stabilizing agent, water-holding agent, thickener, nutraceutical ingredient, fat replacer
	◆ Immunostimulant, cryoprotectant for probiotics
	◆ Triglyceride as well as LDL cholesterol-lowering agent
	◆ Mycotoxins adsorption
Proteins and functional peptides	◆ Antioxidant activity, antiulcer activity, antiproliferative activity, ACE-inhibitory peptides (antihypertensive effect)
Yeast extract	◆ Source of protein, fat, trehalose, Bvitamins
	◆ Source of essential amino acids as well as flavor enhancer amino acids (glycine, alanine, glutamic acid and aspartic acid)
	◆ Source of macrominerals (K, Na, Ca, Mg) trace elements (Zn, Fe, Mn, Cu, Cr, Co, Mo, Se) and vitamins (B3, B6 and B9)
As functional food ingredient	◆ Source of bioactive ingredients- phenolic acids, flavonoids, carotenoids and peptides
	◆ Improves free amino acid and protein contents
	◆ Essential amino acids
	◆ Gel stabilizer, stabilizer in wine
	◆ Emulsification activity
	◆ Hop acids (isoα-, α-, and β-acids)
As fermentation substrate	◆ Proteolytic enzyme or extracellular enzyme production
	◆ ACE-inhibitory proteins production
	◆ Succinic acid production
	◆ Ethanol production
	◆ Methane (biogas) production
	◆ L-(+)-Lactic acid production
As feed ingredient	◆ Fish and prawn feed, cattle feed, poultry feed, swine feed, feed for edible insects
Miscellaneous	◆ Source of enzymes (e.g. proteases)
	◆ Source of nucleic acids (e.g. flavor-enhancing 5′-nucleotides)
	◆ Biosorption (e.g. Pb removal)
	◆ Flocculant
	◆ Synthesis of nanoparticles
	◆ Phytostimulant
	◆ Bio-oil, activated carbon, hydrochar

valorization approach. Transportation cost, short shelf life, and tedious processing were reported to be the predominant issues associated with the usage of wet SBY in pig nutrition, especially in developing countries (Boateng et al., 2015). Hence, long-term SBY preservation is an another crucial factor for its effective utilization. The necessity of SBY preservation was highlighted by Bednarski, Leman, and Poznanski (1983) and it was claimed to be a predominant factor preventing widespread utilization of SBY. The addition of either beet molasses (in 1:1 ratio) or urea (3%) to yeast pulp has been suggested for osmoactive preservation of SBY (Bednarski et al., 1983).

Apart from economic viability, sensory attributes of valorized product are crucial if it is intended for use in food products. Bitter flavor of SBY, which arises due to cell wall adsorption of hop-derived resins and tannins during fermentation, may be a hurdle for its inclusion in foods. However, in a previous study, a complete debittering of SBY without affecting chemical composition by adjusting temperature and pH of slurry was reported (Nand, 1987). In another study, rotary microfiltration was used for both debittering as well as debris separation in the process of yeast extract production from SBY (Shotipruk, Kittianong, Suphantharika, & Muangnapoh, 2005). They showed that a considerable reduction in bitterness can be obtained by autolysis of cell homogenate prior to filtration and rotary filtration of the homogenate at pH 5.5.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Amorim, M., Pinheiro, H., & Pintado, M. (2019). Valorization of spent brewer's yeast: Optimization of hydrolysis process towards the generation of stable ACE-inhibitory peptides. *LWT-Food Science and Technology, 111*, 77–84. https://doi.org/10.1016/j.lwt.2019.05.011.

Amorim, M. M., Pereira, J. O., Monteiro, K. M., Ruiz, A. L., Carvalho, J. E., Pinheiro, H., & Pintado, M. (2016). Antiulcer and antiproliferative properties of spent brewer's yeast peptide extracts for incorporation into foods. *Food & Function, 7*(5), 2331–2337. https://doi.org/10.1039/C6FO00030D.

Ana, L., Andrei, L., Mircea, O., Cristina, G., & Cristina, D. (2017). Brewer's spent yeast as a potential stimulative agent of rye plantlets. *International Multidisciplinary Scientific GeoConference: SGEM: Surveying Geology & mining Ecology Management, 17*, 27–34. https://doi.org/10.5593/sgem2017H/43.

Bednarski, W., Leman, J., & Poznanski, S. (1983). Osmoactive preservation of brewer's yeasts. *Agricultural Wastes, 8*(3), 143–153. https://doi.org/10.1016/0141-4607(83)90113-0.

Bekatorou, A., Plessas, S., & Mantzourani, I. (2015). Biotechnological exploitation of brewery solid wastes for recovery or production of value-added products. In V. R. Rai (Ed.). *Advances in food biotechnology* (pp. 393–414). Chichester: Wiley Blackwell. https://doi.org/10.1002/9781118864463.ch24.

Boateng, M., Okai, D. B., Frimpong, Y. O., & Zeebone, Y. Y. (2015). Wet brewers' spent grains and wet brewers' spent yeast: Problems associated with their usage and suggested solutions: A case study of the Ejisu-Juaben Municipality of Ghana. *Livestock Research for Rural Development, 27* (Article #5).

Boonyeun, P., Shotipruk, A., Prommuak, C., Suphantharika, M., & Muangnapoh, C. (2011). Enhancement of amino acid production by two-step autolysis of spent brewer's yeast. *Chemical Engineering Communications, 198*(12), 1594–1602. https://doi.org/10.1080/00986445.2011.560219.

Bosco, F., Casale, A., Gribaudo, G., Mollea, C., & Malucelli, G. (2017). Nucleic acids from agro-industrial wastes: A green recovery method for fire retardant applications. *Industrial Crops and Products, 108*, 208–218. https://doi.org/10.1016/j.indcrop.2017.06.035.

Bryant, R. W. R., & Cohen, S. D. (2015). Characterization of hop acids in spent brewer's yeast from craft and multinational sources. *Journal of the American Society of Brewing Chemists, 73*(2), 159–164. https://doi.org/10.1094/ASBCJ-2015-0315-01.

Cao, R., Yang, X., Shang, W., Zhou, Z., Strappe, P., & Blanchard, C. (2017). Functional enrichment of mannanase-treated spent brewer yeast. *Preparative Biochemistry & Biotechnology, 47*(8), 789–794. https://doi.org/10.1080/10826068.2017.1342261.

Castro, C., Pérez-Jiménez, A., Coutinho, F., Pousão-Ferreira, P., Brandão, T. M., Oliva-Teles, A., & Peres, H. (2013). Digestive enzymes of meagre (*Argyrosomus regius*) and white seabream (*Diplodus sargus*). Effects of dietary brewer's spent yeast supplementation. *Aquaculture, 416–417*, 322–327. https://doi.org/10.1016/j.aquaculture.2013.09.042.

Chen, K. Q., Li, J., Ma, J. F., Jiang, M., Wei, P., Liu, Z. M., & Ying, H. J. (2011). Succinic acid production by *Actinobacillus succinogenes* using hydrolysates of spent yeast cells and corn fiber. *Bioresource Technology, 102*(2), 1704–1708. https://doi.org/10.1016/

j.biortech.2010.08.011.
Chia, S. Y., Tanga, C. M., Khamis, F. M., Mohamed, S. A., Salifu, D., Sevgan, S., ... Ekesi, S. (2018a). Threshold temperatures and thermal requirements of black soldier fly *Hermetia illucens*: Implications for mass production. *PLoS One, 13*(11), e0206097. https://doi.org/10.1371/journal.pone.0206097.
Chia, S. Y., Tanga, C. M., Osuga, I. M., Mohamed, S. A., Khamis, F. M., Salifu, D., ... Ekesi, S. (2018b). Effects of waste stream combinations from brewing industry on performance of Black Soldier Fly, *Hermetia illucens* (Diptera: Stratiomyidae). *PeerJ, 6*, e5885. https://doi.org/10.7717/peerj.5885.
Chládek, L., Přikryl, M., & Zeman, J. (2007). The possibility of the use of RNA from brewery spent yeast for enrichment of cattle feed. *Conference proceedings, 3rd international conference TAE 2007* (pp. 178–181). Prague: CULS.
Comelli, R. N., Seluy, L. G., Benzzo, M. T., & Isla, M. A. (2018). Combined utilization of agro-industrial wastewaters for non-lignocellulosic second-generation bioethanol production. *Waste and Biomass Valorization,* 1–11. https://doi.org/10.1007/s12649-018-0391-x.
Costa, A. G., Magnani, M., & Castro-Gomez, R. J. H. (2012). Obtainment and characterization of mannoproteins from brewer's yeast cell wall/Obtencao e caracterizacao de manoproteinas da parede celular de leveduras de descarte em cervejaria. *Acta Scientiarum. Biological Sciences, 34*(1), 77–84.
da Silva Araújo, V. B., de Melo, A. N. F., Costa, A. G., Castro-Gomez, R. H., Madruga, M. S., de Souza, E. L., & Magnani, M. (2014). Followed extraction of β-glucan and mannoprotein from spent brewer's yeast (*Saccharomyces uvarum*) and application of the obtained mannoprotein as a stabilizer in mayonnaise. *Innovative Food Science & Emerging Technologies, 23*, 164–170. https://doi.org/10.1016/j.ifset.2013.12.013.
da Silva Guedes, J., Pimentel, T. C., Diniz-Silva, H. T., da Cruz Almeida, E. T., Tavares, J. F., de Souza, E. L., ... Magnani, M. (2019). Protective effects of β-glucan extracted from spent brewer yeast during freeze-drying, storage and exposure to simulated gastrointestinal conditions of probiotic lactobacilli. *LWT-Food Science and Technology, 116*, 108496. https://doi.org/10.1016/j.lwt.2019.108496.
de Melo, A. N. F., de Souza, E. L., da Silva Araujo, V. B., & Magnani, M. (2015). Stability, nutritional and sensory characteristics of French salad dressing made with mannoprotein from spent brewer's yeast. *LWT-Food Science and Technology, 62*(1), 771–774. https://doi.org/10.1016/j.lwt.2014.06.050.
Duda-Chodak, A., Tarko, T., & Milotta, K. (2012). Applicability of different kinds of yeast biomass to lead removal from water. *Journal of Elementology, 17*(1), 7–18.
Ferreira, I.M.P.L.V.O., Pinho, O., Vieira, E., & Tavarela, J. G. (2010). Brewer's *Saccharomyces* yeast biomass: Characteristics and potential applications. *Trends in Food Science & Technology, 21*(2), 77–84. https://doi.org/10.1016/j.tifs.2009.10.008.
George, C., Wagner, M., Kücke, M., & Rillig, M. C. (2012). Divergent consequences of hydrochar in the plant–soil system: Arbuscular mycorrhiza, nodulation, plant growth and soil aggregation effects. *Applied Soil Ecology, 59*, 68–72.
Gonçalves, G. D. C., Nakamura, P. K., Furtado, D. F., & Veit, M. T. (2017). Utilization of brewery residues to produces granular activated carbon and bio-oil. *Journal of Cleaner Production, 168*, 908–916. https://doi.org/10.1016/j.jclepro.2017.09.089.
Gondwe, T. N. P., Mtimuni, J. P., & Safalaoh, A. C. L. (1999). Evaluation of brewery by-products replacing vitamin premix in broiler finisher diets. *Indian Journal of Animal Sciences, 69*(5), 347–349.
Halloran, A., Roos, N., Eilenberg, J., Cerutti, A., & Bruun, S. (2016). Life cycle assessment of edible insects for food protein: a review. *Agronomy for Sustainable Development, 36*, 57. https://doi.org/10.1007/s13593-016-0392-8.
Harlow, B. E., Bryant, R. W., Cohen, S. D., O'connell, S. P., & Flythe, M. D. (2016). Degradation of spent craft brewer's yeast by caprine rumen hyper ammonia-producing bacteria. *Letters in Applied Microbiology, 63*(4), 307–312. https://doi.org/10.1111/lam.12623.
Huang, K., Gao, J. Y., Ma, S., & Lu, J. J. (2012). Optimising separation process of protein and polysaccharide from spent brewer's yeast by ultrafiltration. *International Journal of Food Science & Technology, 47*(6), 1259–1264. https://doi.org/10.1111/j.1365-2621.2012.02967.x.
Huige, N. (2006). Brewery by-products and effluents. In F. G. Priest, & G. G. Stewart (Eds.). *Handbook of Brewing* (pp. 656–707). (2nd ed.). Boca Raton, FL, USA: Taylor & Francis Group.
Jacob, F. F., Striegel, L., Rychlik, M., Hutzler, M., & Methner, F. J. (2019a). Spent yeast from brewing processes: A biodiverse starting material for yeast extract production. *Fermentation, 5*(2), 51. https://doi.org/10.3390/fermentation5020051.
Jacob, F. F., Striegel, L., Rychlik, M., Hutzler, M., & Methner, F. J. (2019b). Yeast extract production using spent yeast from beer manufacture: influence of industrially applicable disruption methods on selected substance groups with biotechnological relevance. *European Food Research and Technology, 245*(6), 1169–1182. https://doi.org/10.1007/s00217-019-03237-9.
Jiang, M., Chen, K., Liu, Z., Wei, P., Ying, H., & Chang, H. (2010). Succinic acid production by *Actinobacillus succinogenes* using spent brewer's yeast hydrolysate as a nitrogen source. *Applied Biochemistry and Biotechnology, 160*(1), 244–254. https://doi.org/10.1007/s12010-009-8649-1.
Jung, E. Y., Lee, H. S., Choi, J. W., Ra, K. S., Kim, M. R., & Suh, H. J. (2011). Glucose tolerance and antioxidant activity of Spent Brewer's yeast hydrolysate with a high content of cyclo-his-pro (CHP). *Journal of Food Science, 76*(2), C272–C278. https://doi.org/10.1111/j.1750-3841.2010.01997.x.
Kabugo, S., Mutetikka, D., Mwesigwa, R., Beyihayo, G. A., & Kugonza, D. R. (2014). Utilization of spent brewer's yeast as a protein substitute for fish meal in diets of growing pigs. *African Journal of Agricultural Science and Technology (AJAST), 2*(5), 116–121.
Kawa-Rygielska, J., & Pietrzak, W. (2014). Ethanol fermentation of very high gravity (VHG) maize mashes by *Saccharomyces cerevisiae* with spent brewer's yeast supplementation. *Biomass and Bioenergy, 60*, 50–57. https://doi.org/10.1016/j.biombioe.2013.10.028.
Kerr, E. D., & Schulz, B. L. (2016). Vegemite beer: Yeast extract spreads as nutrient supplements to promote fermentation. *PeerJ, 4*(e), 2271. https://doi.org/10.7717/peerj.2271.
Lamoolphak, W., Goto, M., Sasaki, M., Suphantharika, M., Muangnapoh, C., Prommuag, C., & Shotipruk, A. (2006). Hydrothermal decomposition of yeast cells for production of proteins and amino acids. *Journal of Hazardous Materials, 137*(3), 1643–1648. https://doi.org/10.1016/j.jhazmat.2006.05.029.
Levic, J., Djuragic, O., & Sredanovic, S. (2010). Use of new feed from brewery by-products for breeding layers. *Romanian Biotechnological Letters, 15*(5), 5559–5565.
Liepins, J., Kovačova, E., Shvirksts, K., Grube, M., Rapoport, A., & Kogan, G. (2015). Drying enhances immunoactivity of spent brewer's yeast cell wall *β*-D-glucans. *Journal of Biotechnology, 206*, 12–16. https://doi.org/10.1016/j.jbiotec.2015.03.024.
Liu, D., Ding, L., Sun, J., Boussetta, N., & Vorobiev, E. (2016). Yeast cell disruption strategies for recovery of intracellular bio-active compounds—A review. *Innovative Food Science & Emerging Technologies, 36*, 181–192. https://doi.org/10.1016/j.ifset.2016.06.017.
Liu, H., Lin, J. P., Cen, P. L., & Pan, Y. J. (2004). Co-production of *S*-adenosyl-L-methionine and glutathione from spent brewer's yeast cells. *Process Biochemistry, 39*(12), 1993–1997. https://doi.org/10.1016/j.procbio.2003.09.031.
Liu, J. Q., Huo, J. C., Lei, Y. L., & Li, X. (2010). Preparation of a novel protein foaming agent for concrete and its performance. *Modern Chemical Industry, 30*(3), 54–56.
Marinescu, G., Stoicescu, A., & Patrascu, L. (2011). The preparation of mayonnaise containing spent brewer's yeast β-glucan as a fat replacer. *Romanian Biotechnological Letters, 16*(2), 6017–6025.
Marson, G. V., da Costa Machado, M. T., de Castro, R. J. S., & Hubinger, M. D. (2019). Sequential hydrolysis of spent brewer's yeast improved its physico-chemical characteristics and antioxidant properties: A strategy to transform waste into added-value biomolecules. *Process Biochemistry, 84*, 91–102. https://doi.org/10.1016/j.procbio.2019.06.018.
Martins, Z. E., Pinho, O., & Ferreira, I.M.P.L.V.O. (2018). Impact of new ingredients obtained from brewer's spent yeast on bread characteristics. *Journal of Food Science and Technology, 55*(5), 1966–1971. https://doi.org/10.1007/s13197-018-3107-0.
Mathias, T. R. S., Alexandre, V. M. F., Cammarota, M. C., de Mello, P. P. M., & Sérvulo, E. F. C. (2015). Characterization and determination of brewer's solid wastes composition. *Journal of the Institute of Brewing, 121*(3), 400–404. https://doi.org/10.1002/jib.229.
Mathias, T. R. S., de Aguiar, P. F., de Almeida e Silva, J. B., de Mello, P. P. M., & Sérvulo, E. F. C. (2017). Brewery waste reuse for protease production by lactic acid fermentation. *Food Technology and Biotechnology, 55*(2), 218–224. https://doi.org/10.17113/ftb.55.02.17.4378.
Mohamad Ansor, N., Abdullah, N., & Aminudin, N. (2013). Anti-angiotensin converting enzyme (ACE) proteins from mycelia of *Ganoderma lucidum* (Curtis) P. Karst. *BMC Complementary and Alternative Medicine, 13*(1), 256. https://doi.org/10.1186/1472-6882-13-256.
Mosai, A. K., Chimuka, L., Cukrowska, E. M., Kotzé, I. A., & Tutu, H. (2020). Removal of platinum (IV) from aqueous solutions with yeast-functionalised bentonite. *Chemosphere, 239*, 124768. https://doi.org/10.1016/j.chemosphere.2019.124768.
Nand, K. (1987). Debittering of spent brewer's yeast for food purposes. *Food/Nahrung, 31*(2), 127–131. https://doi.org/10.1002/food.19870310208.
Nestel, D., & Nemny-Lavy, E. (2008). Nutrient balance in medfly, *Ceratitis capitata*, larval diets affects the ability of the developing insect to incorporate lipid and protein reserves. *Entomologia Experimentalis et Applicata, 126*(1), 53–60. https://doi.org/10.1111/j.1570-7458.2007.00639.x.
Nguyen, N. H., Trinh, L. T., Chau, D. T., Baruah, K., Lundh, T., & Kiessling, A. (2019). Spent brewer's yeast as a replacement for fishmeal in diets for giant freshwater prawn (*Macrobrachium rosenbergii*), reared in either clear water or a biofloc environment. *Aquaculture Nutrition, 25*(4), 970–979. https://doi.org/10.1111/anu.12915.
Oliveira, J. V., Alves, M. M., & Costa, J. C. (2018). Biochemical methane potential of brewery by-products. *Clean Technologies and Environmental Policy, 20*(2), 435–440. https://doi.org/10.1007/s10098-017-1482-2.
Oliveira, R. L., Oliveira, R. J. F., Bezerra, L. R., Nascimento, T. V. C., de Pellegrini, C. B., de Freitas Neto, M. D., ... de Souza, W. F. (2016). Substitution of corn meal with dry brewer's yeast in the diet of sheep. *Revista Colombiana de Ciencias Pecuarias, 29*(2), 99–107. https://doi.org/10.17533/udea.rccp.v29n2a03.
Palasak, T., Sooksai, S., & Savarajara, A. (2019). Comparison of yeast extract prepared by autolysis or steam explosion as a cheap nutrient supplement for very high gravity ethanol fermentation of cassava starch. *Science Asia, 45*(1), 3–9. https://doi.org/10.2306/scienceasia1513-1874.2019.45.003.
Pancrazio, G., Cunha, S. C., de Pinho, P. G., Loureiro, M., Meireles, S., Ferreira, I.M.P.L.V.O., & Pinho, O. (2016). Spent brewer's yeast extract as an ingredient in cooked hams. *Meat Science, 121*, 382–389. https://doi.org/10.1016/j.meatsci.2016.07.009.
Pejin, J., Radosavljević, M., Kocić-Tanackov, S., Marković, R., Djukić-Vuković, A., & Mojović, L. (2019). Use of spent brewer's yeast in L-(+) lactic acid fermentation. *Journal of the Institute of Brewing, 125*(3), 357–363. https://doi.org/10.1002/jib.572.
Petravić-Tominac, V., Zechner-Krpan, V., Berković, K., Galović, P., Herceg, Z., Srečec, S., & Špoljarić, I. (2011). Rhelogical properties, water-holding and oil-binding capacities of particulate β-glucans isolated from spent brewer's yeast by three different procedures. *Food Technology and Biotechnology, 49*(1), 56–64.
Pietrzak, W., & Kawa-Rygielska, J. (2013). Utilization of spent brewer's yeast for supplementation of distillery corn mashes. *Polish Journal of Chemical Technology, 15*(4), 102–106. https://doi.org/10.2478/pjct-2013-0076.
Piotrowska, A., Waszkiewicz-Robak, B., & Swiderski, F. (2009). Possibility of beta-glucan from spent brewer's yeast addition to yoghurts. *Polish Journal of Food and Nutrition Sciences, 59*(4), 299–302.
Podpora, B., Świderski, F., Sadowska, A., Rakowska, R., & Wasiak-Zys, G. (2016). Spent

brewer's yeast extracts as a new component of functional food. *Czech Journal of Food Sciences, 34*(6), 554–563. https://doi.org/10.17221/419/2015-CJFS.
Prochazkova, G., Kastanek, P., & Branyik, T. (2015). Harvesting freshwater *Chlorella vulgaris* with flocculant derived from spent brewer's yeast. *Bioresource Technology, 177*, 28–33. https://doi.org/10.1016/j.biortech.2014.11.056.
Radosavljević, M., Pejin, J., Pribić, M., Kocić-Tanackov, S., Mladenović, D., Djukić-Vuković, A., & Mojović, L. (2020). Brewing and malting technology by-products as raw materials in L-(+)-lactic acid fermentation. *Journal of Chemical Technology & Biotechnology, 95*(2), 339–347. https://doi.org/10.1002/jctb.5878.
Radosavljević, M., Pejin, J., Pribić, M., Kocić-Tanackov, S., Romanić, R., Mladenović, D., ... Mojović, L. (2019). Utilization of brewing and malting by-products as carrier and raw materials in L-(+)-lactic acid production and feed application. *Applied Microbiology and Biotechnology, 103*(7), 3001–3013. https://doi.org/10.1007/s00253-019-09683-5.
Raikos, V., Grant, S. B., Hayes, H., & Ranawana, V. (2018). Use of β-glucan from spent brewer's yeast as a thickener in skimmed yogurt: Physicochemical, textural, and structural properties related to sensory perception. *Journal of Dairy Science, 101*(7), 5821–5831. https://doi.org/10.3168/jds.2017-14261.
Rakin, M., Vukasinovic, M., Siler-Marinkovic, S., & Maksimovic, M. (2007). Contribution of lactic acid fermentation to improved nutritive quality vegetable juices enriched with brewer's yeast autolysate. *Food Chemistry, 100*(2), 599–602. https://doi.org/10.1016/j.foodchem.2005.09.077.
Rodrigues, T. A., Schueler, T. A., da Silva, A. J. R., Sérvulo, E. F. C., & Oliveira, F. J. S. (2019). Valorization of solid wastes from the brewery and biodiesel industries for the bioproduction of natural dyes. *Brazilian Journal of Chemical Engineering, 36*(1), 99–107. https://doi.org/10.1590/0104-6632.20190361s20170608.
Saksinchai, S., Suphantharika, M., & Verduyn, C. (2001). Application of a simple yeast extract from spent brewer's yeast for growth and sporulation of *Bacillus thuringiensis* subsp. *kurstaki*: A physiological study. *World Journal of Microbiology & Biotechnology, 17*, 307–316. https://doi.org/10.1023/A:1016717428583.
Santipanichwong, R., & Suphantharika, M. (2007). Carotenoids as colorants in reduced-fat mayonnaise containing spent brewer's yeast β-glucan as a fat replacer. *Food Hydrocolloids, 21*(4), 565–574. https://doi.org/10.1016/j.foodhyd.2006.07.003.
Satrapai, S., & Suphantharika, M. (2007). Influence of spent brewer's yeast β-glucan on gelatinization and retrogradation of rice starch. *Carbohydrate Polymers, 67*(4), 500–510. https://doi.org/10.1016/j.carbpol.2006.06.028.
Sawisit, A., Seesan, S., Chan, S., Kanchanatawee, S., Jantama, S. S., & Jantama, K. (2012). Validation of fermentative parameters for efficient succinate production in batch operation by *Actinobacillus succinogenes* 130ZT. *Advanced materials research. Vol. 550. Advanced materials research* (pp. 1448–1454). Trans Tech Publications. https://doi.org/10.4028/www.scientific.net/AMR.550-553.1448.
Shotipruk, A., Kittianong, P., Suphantharika, M., & Muangnapoh, C. (2005). Application of rotary microfiltration in debittering process of spent brewer's yeast. *Bioresource Technology, 96*(17), 1851–1859. https://doi.org/10.1016/j.biortech.2005.01.035.
Sombutyanuchit, P., Suphantharika, M., & Verduyn, C. (2001). Preparation of 5′-GMP-rich yeast extracts from spent brewer's yeast. *World Journal of Microbiology and Biotechnology, 17*, 163–168. https://doi.org/10.1023/A:1016686504154.
Sosa-Hernández, O., Parameswaran, P., Alemán-Nava, G. S., Torres, C. I., & Parra-Saldívar, R. (2016). Evaluating biochemical methane production from brewer's spent yeast. *Journal of Industrial Microbiology & Biotechnology, 43*(9), 1195–1204. https://doi.org/10.1007/s10295-016-1792-0.
Spajic, R., Burns, R. T., Moody, L. B., Kralik, D., Poznic, V., & Bishop, G. (2010). Croatian food industry by-products: Co-digestion with swine manure vs. use as liquid animal feed. *Transactions of the ASABE, 53*(4), 1245–1250. https://doi.org/10.13031/2013.32589.
Sreeparvathy, M., & Anuraj, K. S. (2018). Effect of feeding spent brewers yeast on plasma biochemical parameters on cross bred pigs. *Indian Veterinary Journal, 95*(4), 26–29.
Suphantharika, M., Khunrae, P., Thanardkit, P., & Verduyn, C. (2003). Preparation of spent brewer's yeast β-glucans with a potential application as an immunostimulant for black tiger shrimp, *Penaeus monodon*. *Bioresource Technology, 88*(1), 55–60. https://doi.org/10.1016/S0960-8524(02)00257-2.
Tanguler, H., & Erten, H. (2008). Utilisation of spent brewer's yeast for yeast extract production by autolysis: The effect of temperature. *Food and Bioproducts Processing, 86*(4), 317–321. https://doi.org/10.1016/j.fbp.2007.10.015.
Thammakiti, S., Suphantharika, M., Phaesuwan, T., & Verduyn, C. (2004). Preparation of spent brewer's yeast β-glucans for potential applications in the food industry. *International Journal of Food Science & Technology, 39*(1), 21–29. https://doi.org/10.1111/j.1365-2621.2004.00742.x.
Thanardkit, P., Khunrae, P., Suphantharika, M., & Verduyn, C. (2002). Glucan from spent brewer's yeast: Preparation, analysis and use as a potential immunostimulant in shrimp feed. *World Journal of Microbiology and Biotechnology, 18*(6), 527–539. https://doi.org/10.1023/A:1016322227535.
Tian, X., Yang, P., & Jiang, W. (2019). Effect of alkali treatment combined with high pressure on extraction efficiency of β-D-glucan from spent brewer's yeast. *Waste and Biomass Valorization, 10*(5), 1131–1140. https://doi.org/10.1007/s12649-017-0130-8.
Vieira, E., Cunha, S. C., & Ferreira, I.M.P.L.V.O. (2019). Characterization of a potential bioactive food ingredient from inner cellular content of brewer's spent yeast. *Waste and Biomass Valorization, 10*, 3235–3242. https://doi.org/10.1007/s12649-018-0368-9.
Vieira, E. F., Carvalho, J., Pinto, E., Cunha, S., Almeida, A. A., & Ferreira, I.M.P.L.V.O. (2016). Nutritive value, antioxidant activity and phenolic compounds profile of brewer's spent yeast extract. *Journal of Food Composition and Analysis, 52*, 44–51. https://doi.org/10.1016/j.jfca.2016.07.006.
Vieira, E. F., da Silva, D. D., Carmo, H., & Ferreira, I.M.P.L.V.O. (2017). Protective ability against oxidative stress of brewers' spent grain protein hydrolysates. *Food Chemistry, 228*, 602–609. https://doi.org/10.1016/j.foodchem.2017.02.050.
Vieira, E. F., das Neves, J., Vitorino, R., Dias da Silva, D., Carmo, H., & Ferreira, I.M.P.L.V.O. (2016). Impact of *in vitro* gastrointestinal digestion and transepithelial transport on antioxidant and ACE-Inhibitory activities of brewer's spent yeast autolysate. *Journal of Agricultural and Food Chemistry, 64*(39), 7335–7341. https://doi.org/10.1021/acs.jafc.6b02719.
Vieira, E. F., & Ferreira, I.M.P.L.V.O. (2017). Antioxidant and antihypertensive hydrolysates obtained from by-products of cannery sardine and brewing industries. *International Journal of Food Properties, 20*(3), 662–673. https://doi.org/10.1080/10942912.2016.1176036.
Vieira, E. F., Melo, A., & Ferreira, I.M.P.L.V.O. (2017). Autolysis of intracellular content of Brewer's spent yeast to maximize ACE-inhibitory and antioxidant activities. *LWT-Food Science and Technology, 82*, 255–259. https://doi.org/10.1016/j.lwt.2017.04.046.
Vieira, E. F., Pinho, O., & Ferreira, I.M.P.L.V.O. (2017). Bio-functional properties of sardine protein hydrolysates obtained by brewer's spent yeast and commercial proteases. *Journal of the Science of Food and Agriculture, 97*(15), 5414–5422. https://doi.org/10.1002/jsfa.8432.
Vieira, E. F., Van Camp, J., Ferreira, I.M.P.L.V.O., & Grootaert, C. (2018). Protein hydrolysate from canned sardine and brewing by-products improves TNF-α-induced inflammation in an intestinal–endothelial co-culture cell model. *European Journal of Nutrition, 57*(6), 2275–2286. https://doi.org/10.1007/s00394-017-1503-2.
Vitanza, R., Cortesi, A., Gallo, V., Colussi, I., & De Arana-Sarabia, M. E. (2016). Biovalorization of brewery waste by applying anaerobic digestion. *Chemical and Biochemical Engineering Quarterly, 30*(3), 351–357. https://doi.org/10.15255/CABEQ.2015.2237.
Waszkiewicz-Robak, B., & Bartnikowska, E. (2009). Effects of spent brewer's yeast and biological β-glucans on selected parameters of lipid metabolism in blood and liver in rats. *Journal of Animal and Feed Sciences, 18*(4), 699–708. https://doi.org/10.22358/jafs/66443/2009.
Worrasinchai, S., Suphantharika, M., Pinjai, S., & Jamnong, P. (2006). β-Glucan prepared from spent brewer's yeast as a fat replacer in mayonnaise. *Food Hydrocolloids, 20*(1), 68–78. https://doi.org/10.1016/j.foodhyd.2005.03.005.
Xu, X., Pu, Q., He, L., Na, Y., Wu, F., & Jin, Z. (2009). Rheological and SEM studies on the interaction between spent brewer's yeast β-glucans and κ-carrageenan. *Journal of Texture Studies, 40*(4), 482–496. https://doi.org/10.1111/j.1745-4603.2009.00193.x.
Yantcheva, N. S., Karashanova, D. B., Georgieva, B. C., Vasileva, I. N., Stoyanova, A. S., Denev, P. N., ... Slavov, A. M. (2019). Characterization and application of spent brewer's yeast for silver nanoparticles synthesis. *Bulgarian Chemical Communications, 51*(Special Issue D), 173–177.
Yiannikouris, A., Francois, J., Poughon, L., Dussap, C. G., Bertin, G., Jeminet, G., & Jouany, J. P. (2004). Alkali extraction of β-D-glucans from *Saccharomyces cerevisiae* cell wall and study of their adsorptive properties toward zearalenone. *Journal of Agricultural and Food Chemistry, 52*(11), 3666–3673.
Yoo, M. S., & Lee, Y. T. (2007). Pasting properties of crude β-glucan from spent brewer's yeast on wheat flour and starch. *Food Science and Biotechnology, 16*(3), 485–488.
Zechner-Krpan, V., Petravić-Tominac, V., Galović, P., Galović, V., Filipović-Grčić, J., & Srečec, S. (2010). Application of different drying methods on β-glucan isolated from spent brewer's yeast using alkaline procedure. *Agriculturae Conspectus Scientificus, 75*(1), 45–50.
Zechner-Krpan, V., Petravić-Tominac, V., Panjkota-Krbavčić, I., Grba, S., & Berković, K. (2009). Potential application of yeast β-glucans in food industry. *Agriculturae Conspectus Scientificus, 74*(4), 277–282.